Insights into wind sites: critically assessing the innovation, cost, and performance dynamics of global wind energy development

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Insights into Wind Sites: Critically assessing the innovation, cost, and performance dynamics of global wind energy development

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Abstract: Reliable empirical data on the siting characteristics and operational performance of wind farms are scarce. Knowing more about the technical characteristics of wind farms provides insight into the business mindset of wind farm developers, which can be useful for policymakers or researchers who are intent on designing policy in a way to optimize wind farm investment by creating better alignment between the investment patterns sought by developers and government support designed to attract investment. This study draws on a unique dataset from 32 wind farms, 20 onshore and 12 in forested areas with a total of more than 2.5 GW installed wind capacity to explore development patterns. The paper examines four hypotheses related to characteristics of wind farms in emerging markets and investigating how project delays and progressive technological enhancements shape wind farm development. In this paper, we explain these results and conclude by extracting lessons from this analysis for creating wind power policy ~~that is in better alignment~~better aligned with developers' interests.

Keywords: Wind Power, Energy Trends, Energy Policy, Performance Patterns

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1. Introduction

Wind power has been recognized as one of the most promising technologies in the transition towards electricity generated by low-carbon resources (Masters, 2013; Rand and Hoen 2017). Even more than a decade ago, basing projections on technology that is now outdated, 20% of the world's realizable wind energy potential was considered to be enough to satisfy the world's energy needs (Archer and Jacobson, 2005).

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And, a cite to Scott's wind power book with Oxford would make sense also

https://global.oup.com/academic/product/wind-power-politics-and-policy-9780199862726?cc=gb&lang=en&

also let's cite this:

Joseph Rand, Ben Hoen, Thirty years of North American wind energy acceptance research: What have we learned?, Energy Research & Social Science, Volume 29, July 2017, Pages 135-148

More recently, the emergence of commercially viable wind energy systems have fueled a market boom (Sovacool and Enevoldsen, 2015). The world's installed wind power capacity has blossomed from 17.4 GW in 2000 to 486 GW in 2016 (GWEC, 2017). Moreover, wind power installations which were more or less limited to Western Europe, USA, India, and China just 10 years ago (GWEC, 2007) have now diffused to more than 100 countries (GWEC, 2017).

As a welcome side effect of this growth, the industry now employs more than 1 million workers (IRENA, 2015). In testament to the comparative rise of wind power as an important source of employment, in the United States, the wind power sector employed 88,000 workers in 2015, compared to just 67,929 employed in the coal mining sector (AWEA, 2016; Lovins, 2017).

Despite the allure of wind power, however, policymakers and even the research community in general know little about why wind farms develop in the manner that they do. In many economic sectors, understanding development patterns are important if policymakers are to create supportive

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policy measures (Jefferson, 2014; Kelsey and Meckling 2018). For example, in agriculture, it would be imprudent to create policy which supports certain crops over others without understanding how and why farmers plant the crops they do. Similarly, in regard to wind farm development, successful diffusion is fortified by establishing conditions that are most conducive to attracting investment while ensuring that other aspects of social welfare are not undermined by the development (Enevoldsen and Sovacool, 2016). By extension, it is intuitively logical that as wind power markets evolve, land scarcity concerns rise and "Not in My Back Yard" (NIMBY) threats elevate, policies might need to be devised to nudge developers into developing projects that might not otherwise materialize under free market conditions (Valentine, 2014). In some markets the socio-political and cultural factors are becoming just as important as wind resources~~speeds~~ (Khan, 2003; Brinkman and Hirsh 2017; Hirsh and Sovacool 2013), as decades of innovative research has rendered it possible for wind turbine to operate in a wide range of wind conditions (Sovacool & Enevoldsen, 2015) including low – and extreme wind speeds. However, as stated by Jefferson (2018) wind project developers have to achieve certain capacity factors, in order to succeed with a business. It is therefore critical when lack of socio-political support push new developments to complex areas where wind resource assessments are more unsecure (Enevoldsen, 2016).

Previous research suggests that development patterns in the electricity sector might not be solely driven by technological or economic factors (Geels et al., 2017; Sovacool et al., 2017). Yet further empirical research is needed to support suppositions on how wind farms are designed and configured. Until the impacts of market and policy dynamics on wind farm developer behavior are better clarified through empirical research, it is difficult to optimize both technological design and policy in order to promote developments that serve the needs of communities while delivering

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Commented [b3]: Use "speeds" again in the sentnce, thought this diverisfied it a bit

Commented [b4]: Two new refs to go with the "cultural" argument in the sentence:

Joshua T. Brinkman, Richard F. Hirsh, Welcoming Wind Turbines and the PIMBY ("Please in My Backyard") Phenomenon: The Culture of the Machine in the Rural American Midwest, Technology and Culture, Volume 58, Number 2, April 2017, pp. 335-367.

Hirsh, RF and BK Sovacool. "Wind Turbines and Invisible Technology: Unarticulated Reasons for Local Opposition to Wind Energy," Technology & Culture 54(4) (October, 2013), pp. 705-734.

much needed clean energy into the grid, which is an emerging challenge for all renewables (Jefferson, 2016).

In contributing to this challenge, this article critically examines operational data from 32 wind farms with a total of more than 2.5 GW installed wind capacity. It does so with the aim of better understanding wind power development patterns so that policymakers, community planners, engineers, and analysts can harness and optimize policies and development standards that will help them to encourage wind farm developments that best balance community expectations and economic performance. The purpose of the paper can therefore be articulated as the following four hypotheses or preconceptions which are sought to be tested through the operational data:

1. In nations that have low levels of installed wind power capacity, developers will be more risk averse causing initial projects to be smaller.
2. Due to elevated concerns over avian mortality and desires to minimize deforestation, wind farms in forested areas should have fewer turbines. However, these turbines should deliver more output per turbine.
3. Project development lags ~~along with~~ and delays in ~~the turbine sales cycle~~logistics and sales channels will result~~s~~ in wind farms that are developed with ~~outmoded~~ outdated technology.
4. New wind farm sites should produce more power in aggregate because developers can use turbines with enhanced power capture capabilities and improved designs.

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Also changed in Table

2. Research Design and Methods

The primary source of data for this study is ~~a proprietary~~an original dataset concerning the configurations and 2015 performance characteristics of 32 globally situated wind farms, including 20 "conventional" onshore wind farms (onshore farms) spread across five continents and 12 wind

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farms in forested areas (forested-area farms) ~~that are~~ primarily located in Northern Europe. Due to confidentiality agreements with the data providers, the project names and specific locations have been anonymized. We have decided to separate the forested-area farms from the onshore farms because we thought that ~~the regional specificity of the forested area farms and~~ the relative immaturity of this emerging market pattern might yield different development patterns that would obscure our findings if treated together. The reason being that wind turbines operating in forested areas tends to have unique performance patterns (Enevoldsen and Valentine, 2016), which are caused by the changes in wind conditions in the roughness sub-layer above forest canopies (Arnqvist et al., 2015; Enevoldsen, 2016). The forest configurations can furthermore be considered a novel and emerging market pattern within well-established and mature wind markets, and also more or less the only onshore configuration in countries well covered by forest.

Figure 1 and 2 illustrate the aggregated profiles of these wind farms, delineated by region and described in terms of average wind farm size (MW) (Fig. 1) and average annual energy production per wind farm (MWh) (Fig. 2).

Figure 1: Average Wind Farm Size within the Dataset (MW)

~~**INSERT FIGURE 1 HERE**~~

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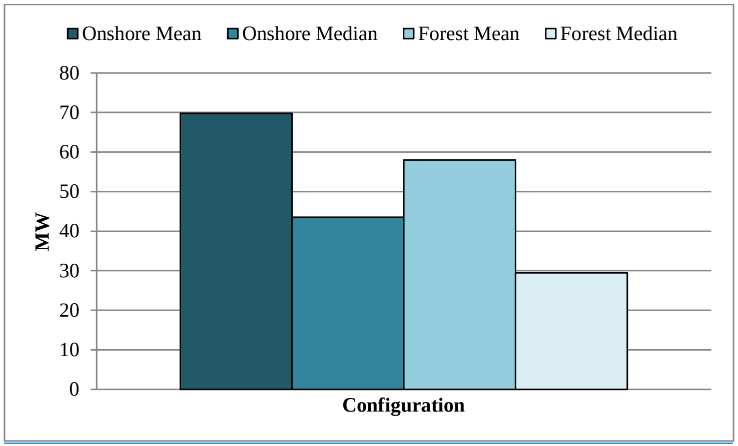
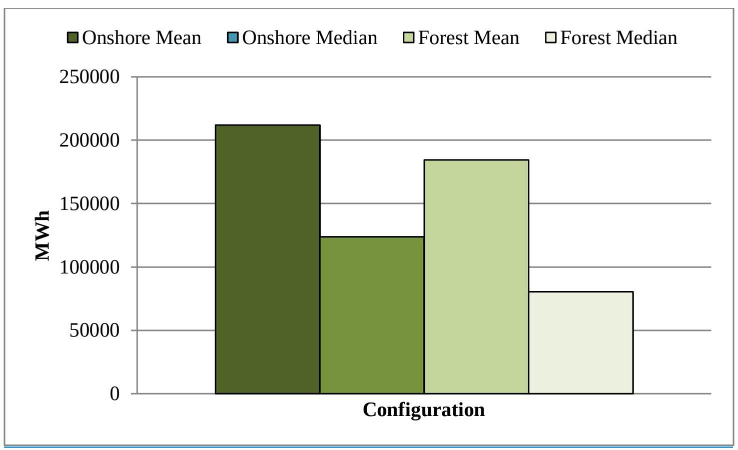


Figure 2: Annual Wind Farm Energy Production within the Dataset (MWh)

~~**INSERT FIGURE 2 HERE**~~



The data encapsulated in these figures suggest that the onshore farms possess higher capacity (MW) than forested-area farms do. Evaluating the reason for this difference can help policymakers (and others) better understand the mindset of developers, the drivers which influence project development and the factors that might have to be managed to catalyze desirable patterns of wind power development. This insight inspired the creation of four hypotheses related to development patterns that could be empirically evaluated by digging further into the data set to investigate disparities at the individual wind farm level. The hypotheses analyzed in this study were largely chosen because the proprietary data we had access to could inform the analysis. Although research is typically driven by research questions, which then dictate methods to be used, in this study the approach was turned on its head to leverage our unique access to industry data – making it a data driven or grounded approach. Through meetings with developers and through our own set of experiences in the industry, we feel that the preconceptions we put forth in Table 1 are all of policy importance. To ensure industry relevance, aside from interpreting our statistical analysis, we met with nine wind power developers in order to get experiential assistance in interpreting the findings.

Table 1 Wind Power Development Hypotheses

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H	Topic	Preconceptions	Evaluation Basis
1	**Emerging markets**	In nations that have low levels of installed wind power capacity, developers will be more risk averse causing initial projects to be smaller.	Examine each wind farm and document the year they were put into operations. If total installed MW wind capacity in the nation at the time was <1000 MW, we code the farm in question as "0" (new market); if >1000 MW, we code it as "1" (an established market). We then test to see if the average for 0's in terms of installed MW per farm is less than the average for conditions labelled "1".
2	**Forested areas**	Due to elevated concerns over avian mortality and desires to minimize deforestation, wind farms in forested areas should have fewer turbines. However, these turbines should deliver more output per turbine.	The number of turbines in wind farms in forested areas should be smaller when compared to onshore wind farms in "conventional" areas. However, power output per turbine should be greater in forested areas.
3	**Project delays**	Project development lags and delays in logistics and sales channels will result in wind farms	Working with data on when a wind farm became operational, what technologies were already on the market at the time and what type of wind turbine was actually installed,

		that are developed with outdated technology.	gives us insight into how significant the project lag was in deterring the use of best available technology.
4	**Technological innovation**	New wind farm sites should produce more power in aggregate because developers can use turbines with enhanced power capture capabilities and improved designs..	Evaluate this by comparing i) aggregate output trends, ii) the size of wind farms (total turbines), and iii) output per turbine.

~~**INSERT TABLE 1 HERE**~~

To evaluate the emerging market hypothesis (H1), we employed a comparison of means, medians and standard deviations. For each farm, we first ascertained the aggregate level of installed wind power capacity in the nation in question at the time the project was completed. When this level was under 1000 MW, we assigned a delineation variable of "0" to the wind farm under analysis, indicating that the wind farm was being developed when the nation was still considered to be an emerging nation when it came to wind power development. When the level in the nation was 1000 MW or over, we assigned a delineation variable of "1" to the wind farm under analysis, indicating that the wind farm was developed in a nation where wind power had diffused to a level of installed capacity that was deemed to be sufficient to consider the nation as a mature wind market. The intension of applying delineation variables was to allow us to separate mature from immature wind markets, despite including no mathematical function.

Our preconception was considered supported if to a high degree of statistical certainty, the average aggregate output of wind farms in emerging wind power nations was lower than the average aggregate output of wind farms in mature wind power nations. The 1000 MW figure was an admittedly arbitrary description but the rationale of this was vetted by ascertaining the opinions of two wind power developers, who claimed that an installed capacity of more than 1 GW would require a national setup and thereby also experienced stakeholders.

We also employed a comparison of means, medians and standard deviations to evaluate the forested area hypothesis (H2). From our data set, we separated the 12 forested-area wind farms from the 20 "conventional" sites (onshore farms) because there is a clear developmental distinction between these two types of projects (as different siting regulations apply). We then accessed data on the number of turbines in each wind farm and compared the means, medians and standard deviations of the two types of developments to see if the forested area wind farms had fewer turbines, which we speculated could be due to the physical limitations of creating projects in forested (ecologically sensitive) areas. We also sought to test if the comparative disparity in number of turbines was partially offset by higher output per turbine – thereby rationalizing the investment decision. Adding validity to this supposition is an engineering norm that in forested areas, turbines are typically much larger and the wind systems are set on much higher towers to get above the forest canopy, which have been applied widely in Scandinavia. Consequently, we would expect the output per turbine in forested-areas to be much higher.

To evaluate the project delays and technological lag hypothesis (H3), we conducted an analysis of variances (ANOVA) wherein we subtracted the name plate capacity and rotor diameter of the most advanced turbine at each wind farm from the name plate capacity and rotor diameter of the most advanced turbine available at the time of project inception. We then averaged the variances for each farm. We acknowledge that project delays alone would not be the sole explanation for wind developers to pass up utilizing the newest technology. Indeed, in interviews with wind developers, one suggested that as new technology is introduced, the cost of outmoded technologies typically fall. In other words a technological lag exists as the cost of new products drop over time. Furthermore, curtailments of the operating wind turbine can be taken into consideration after years of operating, due to e.g. increased noise emission, bird collisions, and other unforeseen events.

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Therefore, the insight that this test provides is whether or not the newest technology is being incorporated into a project and if not, how great on average is the innovation lag when compared to output energy of the newest available technology.

To evaluate the technological innovation hypothesis (H4), we employed correlation analysis to evaluate aggregate energy output (MWh) totals for each farm with the independent variable being year of commencement of project operation. We would expect that over time, wind farms on average should generate higher energy output per installed MW thanks to enhanced technology. However, we also acknowledge that there is a competing perspective that this might not be the case because in response to bigger and better machines, developers might simply build smaller wind farms. Some possible reasons for this might include a desire to mitigate NIMBY opposition, grid limitations that restrict the growth of larger wind farms or the financial cost of purchasing bigger and better turbine that necessitates trade-offs in terms of project size.

In order to triangulate our findings for H4, we also ran a correlation analysis to evaluate the number of total wind turbines installed in the wind farms in our data set and a correlation analysis of the output per turbine at the wind farms in our data set. This was intended to help us evaluate the competing perspective that wind projects are using less space with more concentrated generation of energy, should this factor emerge in the first test (aggregate wind farm energy generation) as being a possibility.

In regard to interpretation of our correlation analyses, in line with Field (2009) as well as Sovacool and Walter (2018), we categorize a small significant effect as ($R^2 <= 0.01$), a medium significant effect as ($R^2 >= 0.09$), and a large significant effect ($R^2 >= 0.25$). In addition to a regression analysis, P-values were calculated to test the probability of the correlation underpinning each

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Sovacool, BK and G Walter. “Major Hydropower States, Sustainable Development, and Energy Security: Insights from a Preliminary Cross-Comparative Assessment,” Energy 142 (January ,2018), pp. 1074-1082.

preconception as being predictive. For the purposes of our analysis, we conclude that a P-value below 0.05 provides strong indication that the null hypothesis for each evaluation metric is not valid and therefore, the tested relationship is significant.

3. Results and Discussion

3.1 Emerging Markets

In nations that have low levels of installed wind power capacity, developers will be more risk averse causing initial projects to be smaller.

More than 100 countries have wind farms; however, only 24 countries boast installed capacity of more than 1,000 MW in aggregate, and only ~~6~~ six of these countries have more than 10,000 installed MW of wind power. Emerging wind power markets lack two key elements which help attenuate market risk. First, immature wind markets typically ~~lack the track~~have a poor track record of staunch government policy commitment to wind power development that investors seek. As such, developers should intuitively enter into such markets tentatively. Second, due to lack of in-market experience and potentially less well-formed networks, wind developers entering into immature markets face elevated development risks. Projects can be curtailed due to unexpected social opposition or rendered unprofitable due to unanticipated costs arising from project planning inexperience in an immature market. It has been suggested that benefits arising from learning by doing can significantly alter the fortunes of wind projects (Ibenholt, 2002; Qiu and Anadon, 2012). Accordingly, the first preconception that we sought to test was the belief that developers will enter into emerging markets in a more tentative manner in order to attenuate market risk. This preconception has been analyzed using descriptive statistical analyses, presented in table 2 below.

Table 2 Descriptive Statistics for the Aggregate Wind Energy Generation from Wind Farms in Emerging markets Compared to Mature Markets

< 1000 MW	Value (MWh)	>1000 MW	Value (MWh)
Mean	222039	Mean	128706
Standard Deviation	256174	Standard Deviation	105588
Median	99520	Median	94170
Range	936883	Range	271306
Minimum	28661	Minimum	22614
Maximum	965544	Maximum	293920
Count	25	Count	7

~~INSERT TABLE 2 HERE~~

A key insight from Table 2 is that the majority of projects (78 %) were commercialized at a time where the host country had less than 1,000 MW of installed wind capacity. Data do not support the hypothesis that projects in immature markets will be smaller. Indeed, the minimum, maximum, mean, and median numerical values for wind farms in immature markets exceed the comparable values for the mature markets.

It should be further noted that the dataset used for this analysis consisted of two wind power configurations, 1) onshore non-forested areas, and 2) onshore forested-areas. Therefore, we re-ran the analysis for each configuration (onshore and onshore-forested) separately to ensure that one configuration was not distorting the aggregate data. Table 3 presents the results.

Table 3 Descriptive Statistics for the Aggregate Wind Energy Generation from Wind Farms in Emerging markets Compared to Mature Markets in two configurations

Onshore			
< 1000 MW	Value (MWh)	>1000 MW	Value (MWh)
Mean	255306	Mean	110575
Standard Deviation	249453	Standard Deviation	103040
Median	153071	Median	76435
Range	834827	Range	271306
Minimum	44394	Minimum	22614
Maximum	879221	Maximum	293920
Count	14	Count	6

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Forested			
< 1000 MW	**Value (MWh)**	**>1000 MW**	**Value (MWh)**
Mean	179700	Mean	237495
Standard Deviation	270341	Standard Deviation	
Median	71654	Median	237495
Range	936883	Range	
Minimum	28662	Minimum	
Maximum	965545	Maximum	
Count	11	Count	1

~~**INSERT TABLE 3 HERE**~~

The conclusions we draw from Table 3 is that when it comes to conventional onshore wind farms, developers are not more risk averse in emerging markets. On the contrary, initial projects are significantly larger in such markets. For the onshore-forested sample represented in Table 3, the fact that only one wind farm was established in a nation with over 1,000 MW of installed capacity statistically prevents statistically valid comparison. The first hypothesis has therefore not been supported by the data set that we had access to.

In trying to rationalize why the data does not seemingly support our preconception, we asked two wind farm developers for insight into why wind farms in emerging markets tended to be larger in size. One suggested that the risk of entering a new market were elevated. Consequently, entries were not undertaken unless the incentives were high. The allure of building larger wind farms and reaping added profits would constitute such an incentive. Another developer suggested that often in emerging markets, wind farm projects were taken over mid-stream when original developers ran into financial problems and approached established developers in other markets to bail them out by infusing higher levels of capital and creating projects that exhibited better economies of scale.

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3.2 Forested Areas

Due to elevated concerns over avian mortality and desires to minimize deforestation, wind farms in forested areas should have fewer turbines. However, these turbines should deliver more output per turbine.

Wind project development in forested areas is complicated by trees and other natural foliage which can degrade wind quality. In response to this, wind turbines manufacturers produce higher towers to harvest wind that is less hindered by the drag of the forest canopy (Enevoldsen and Valentine, 2016), which has been observed in Scandinavia unless limited by height restrictions (Enevoldsen, 2016). Furthermore, elevated environmental concerns should encourage developers to place greater space between the turbines. For these reasons, we expect wind farms in onshore-forested areas to be smaller than wind farms in onshore, non-forested areas. The results of our analysis for vetting this hypothesis are presented in Table 4.

Table 4 Descriptive Statistics for the Number of Turbines in Wind Farms in Forested Areas Compared to non-forested Areas

Forested Descriptive Statistics	**Value (WTGs)**	**Onshore Descriptive Statistics**	**Value (WTGs)**
Mean	23	Mean	29
Standard Deviation	24	Standard Deviation	24
Median	13	Median	19
Range	86	Range	86
Minimum	4	Minimum	4
Maximum	90	Maximum	90
Count	12	Count	20

~~INSERT TABLE 4 HERE~~

Analysis of the data presented in Table 4 confirms that within our data set, wind projects in forested-areas have fewer wind turbines. It is furthermore noteworthy to find that the range, and minimum and maximum number of wind turbines per wind farm is the same for both configurations, which strengthens the basic of the comparative analysis.

As mentioned earlier, it was further postulated that wind farms in forested-areas should produce more energy per turbine because taller towers associated with such projects enable the use of larger, more efficient wind systems. Table 5 compares the descriptive statistical measures for the aggregate annual energy production (MWh) per turbine from the forested and non-forested onshore wind projects in order to evaluate this preconception.

Table 5 Descriptive Statistics for the Aggregate MWh Per Turbine in Forested Areas Compared to non-forested areas

Forested Descriptive Statistics	Value (MWh)	Onshore Descriptive Statistics	Value (MWh)
Mean	7019	Mean	7033
Median	6737	Median	6823
Standard Deviation	1332	Standard Deviation	2189
Range	5152	Range	7491
Minimum	5575	Minimum	3678
Maximum	10728	Maximum	11169
Count	12	Count	20

~~**INSERT TABLE 5 HERE**~~

The results introduced in Table 5 indicates that despite a greater standard deviation, the wind turbines operating in non-forested areas and forested areas exhibit similar energy output profiles when measured on a per installed MW basis. Therefore, the data do not support our preconception. However, due to the high standard deviation of both samples, the data cannot categorically refute the hypothesis either. The findings presented in Table 5 have been depicted in the graph in Figure 3 to visually illustrate the relationship between the size of a wind farm (number of Wind Turbine Generators (WTGs)) and the annual energy production (MWh) per installed MW.

Figure 3 Relationship between the size of the wind farm, and the efficiency per installed wind turbine

~~**INSERT FIGURE 3 HERE**~~

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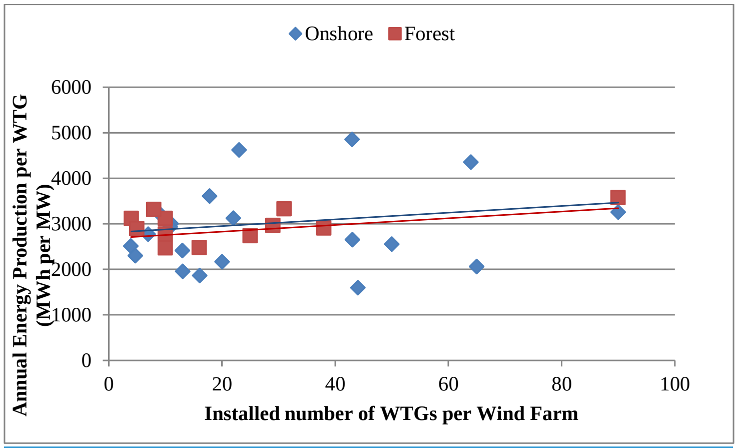

The trend lines in Figure 3 reveal a slightly higher production per installed wind turbine for forested sites. However, since the development of wind farms in forested areas is a more recent phenomenon, we speculate that the relative newness of the technology employed in forested-areas might account for this slight discrepancy. Interestingly, there appears to be little correlation between efficiency (MWh per installed MW) and the installed number of wind turbines for the non-forested areas (R^2 = 0.04), whereas wind farms in forested areas tend to exhibit higher correlation between the number of turbines and the overall power output (R^2 = 0.27).

3.3 Project Delays

Project development lags and delays in logistics and sales channels will result in wind farms that are developed with outdated technology. ~~*Due to project development lags and delays in the turbine sales cycle, wind farms are developed with outmoded technology.*~~

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According to some of the wind developers that we interviewed, the wind farm planning process can extend up to 10 years in extreme cases. Project delays have been caused by factors such as social opposition (that developers interviewed attribute to lack of public involvement) or political systems which inadvertently fuel opposition due to poor policy planning (Valentine, 2014). We speculate that project delays lock developers in to technologies that might be outmoded by the time the project is realized.

Two developers working in different markets described the importance of sticking with the technology that was selected at the project inception stage. If new technology is introduced, often the project approval process must start anew, leading to further project delays. The same developers also estimated that the average time of a wind project from finding the land to installing the turbine ranges between 3-7 years, exacerbating the extent to which technology could become outmoded by the time the project is realized.

When examining the evolution of wind turbine technologies, it is clear that wind turbine technology continues to progress at a linear pace in terms of increases in baseplate capacity (kW), height, and rotor diameter. Figure 4 below depicts the evolution of new onshore wind turbine technologies for the period 2009-2017. This analysis incorporates data from seven different manufacturers.

Figure 4 Development of wind turbine size (rotor diameter (m) and baseplate capacity (KW)) over time

~~**INSERT FIGURE 4 HERE**~~

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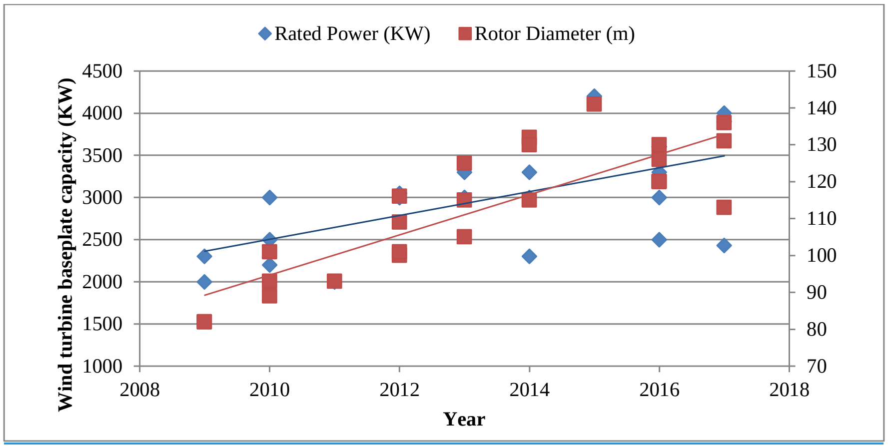


It merits highlighting that in practice, some developers prefer wind turbines with lower rated power and shorter rotor diameters, due to grid requirements, tip height restrictions, support instruments, wind conditions, etc. Nevertheless, the trend in Figure 4 illustrates a constant technological trend towards larger wind turbines (with R^2 = 0.70 for the associated trends line) and larger rotor diameters (with R^2 = 0.38 for the associated trend line).

Experience tells us that wind power developers are aware of new wind turbine models that come to market. However, because of project delays, we expect to find a significant difference between the date that a new model is introduced to the market and the date that these models are actually adopted for use in projects. Table 6 presents an analysis of descriptive statistics which attempt to quantify the difference between technological market introduction and project adoption.

Table 6 Descriptive statistics evaluating the difference between wind turbine model introduction and wind farm adoption

Mean	3.9
Median	3.0
Mode	3.0
Standard Deviation	2.0

Range	8.0
Minimum	1.0
Maximum	9.0
Count	32.0

~~INSERT TABLE 6 HERE~~

Table 6 reveals a median difference of 3 years and a mean difference of 3.9 years between the introduction of a new wind turbine model and its diffusion in the form of project adoption. This analysis lends credence to our preconception; however, it is worth noting that the technology lag is not always detrimental to project fortunes. As one developer noted, when new turbines are introduced, the market prices of older turbines tend to drop yielding a financial incentive to employ older technology.

3.4 Technological Innovation

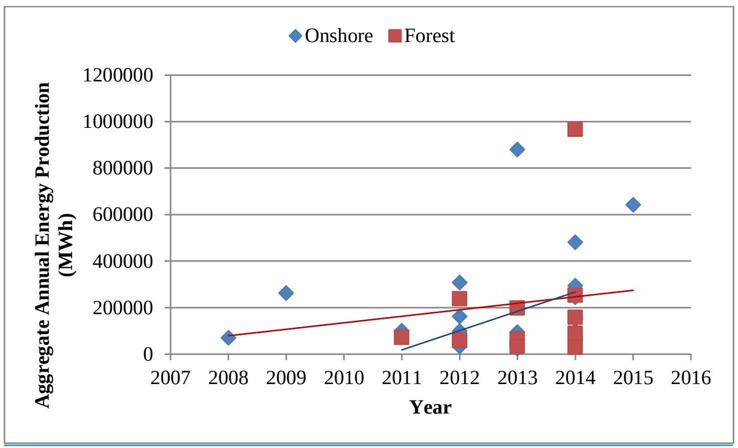
New wind farm sites should produce more power in aggregate because developers can use turbines with enhanced power capture capabilities and improved designs ~~*Newer wind farm sites should produce more energy in aggregate because developers can use turbines with enhanced energy capture capabilities.*~~

Progressive innovation has resulted in an increasing size of rotor diameters and higher towers allowing wind systems to harvest more energy (Paulsen and Thüring, 2015). Wind turbines deployed in 2009 generated 180 times more electricity when compared to the state-of-the-art wind turbine of 1989. More importantly, such increased production came at half the cost (Blanco, 2009). Technological changes have enabled the wind industry to target new locations such as forests and complex terrains. Therefore, given technological progress, it is assumed that newer installations should produce more electricity (MWh) in aggregate.

Figure 5 illustrates the relationship between aggregate wind farm output and date of project operationalization. The analysis has been split into onshore-forested and onshore non-forested in order to reduce any potential statistical confounds caused by including forest wind farms in the data set. This is in response to a concern that forested-area wind farms are newer and subject to learning by doing effects which might influence aggregate wind farm size.

Figure 5 Correlation analysis of aggregate output trends at wind farms over time

~~**INSERT FIGURE 5 HERE**~~

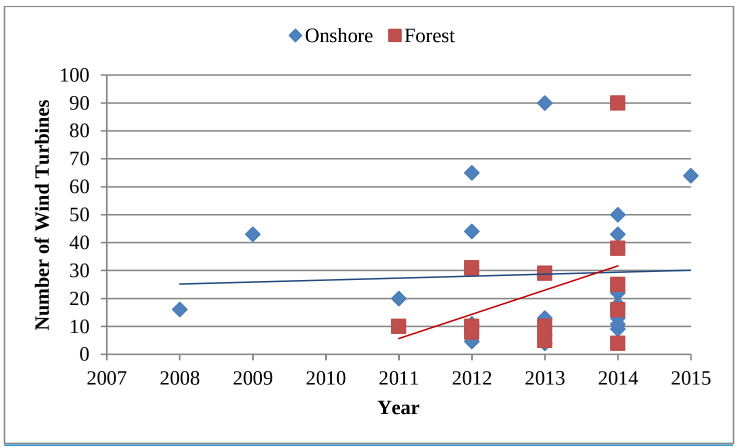


As Figure 5 visually suggests, both configurations of wind farms appear to be increasing in size over the years. Analyzing Figure 5 statistically reveals that date of operationalization might not be the main catalyst influencing wind farm size. For both onshore non-forested (R^2 = 0.05) and forested (R^2 = 0.11) configurations, the R^2 is too low to support the conjecture that the increasing trend is adequately explained by date of operationalization. Therefore, we contend that the data does not support our supposition – newness of project development does not fully explain why wind farm size is increasing. We speculate that other influential factors might include greater confidence in government policies, lower turbine costs (measured on a MWh basis) and greater market maturity that results in higher levels of developer confidence to commit larger amounts of investment to projects. All of these factors merit further analysis in future studies.

One other possible explanation for the aggregate increase in energy output in newer wind farms is that these newer farms are simply using better technology. In other words, the farms are not producing more energy because they are growing in size, they are producing more energy as a result of using better turbines with greater power generation capacity. Since we had access to this data, we felt that this explanation was plausible enough to merit further investigation in the current study. Figure 6 presents the results of our correlation analysis.

Figure 6 Correlation analysis of size of wind farms (total turbines) over time

~~**INSERT FIGURE 6 HERE**~~



As Figure 6 visually suggests, the data are dispersed enough to suggest that the correlation between number of turbines in use and date of project operationalization is tenuous. When examining the R^2, we find that for onshore non-forested wind farms in our data set, the co-efficient of determination is $R^2 = 0.01$. For forested area wind farms in our data set, the co-efficient of

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determination is $R^2 = 0.14$. This suggests that the correlation is indeed tenuous and leads us to conclude that the data does not support our preconception. We conclude that something else other than wind turbine size or output capabilities are catalyzing larger wind farm developments. Likely, the most likely driving factor is market confidence but again, this needs to be empirically tested.

4. Conclusion and Policy Implications

To conclude and summarize, we have examined four preconceptions attributed to global wind power development. The findings summarized in Table 7 show that only two are supported by our data.

Table 7 Summary of Findings

Number	Preconception	Tested by	Hypothesis
1	**Emerging Markets** In nations that have low levels of installed wind power capacity, developers will be more risk averse causing initial projects to be smaller.	descriptive statistics analysis and cluster variance analysis	Not supported
2	**Forested Areas** Due to elevated concerns over avian mortality and desires to minimize deforestation, wind farms in forested areas should have fewer turbines. However, these turbines should deliver more output per turbine.	descriptive statistics analysis and Regression analysis	Fewer turbines supported but better efficiency not supported
3	**Project Delays** Due to a project development lag along with delays in the turbine sales cycle, wind farms are developed with outmoded technology.	descriptive statistics analysis and Regression analysis	Supported
4	**Technological Innovation** New wind farm sites should produce more energy in aggregate because developers can use turbines with enhanced energy capture capabilities.	descriptive statistics analysis and Regression analysis	Not supported

~~**INSERT TABLE 7 HERE**~~

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Regarding the first preconception that the risks associated with emerging markets promote smaller market forays (smaller projects), our data analysis does not support this. ~~This suggests that~~An implication is that adopting policies to drive market diffusion at early stages might not be needed to induce investment in immature markets. This finding ~~, which is supported by the finding from~~is supported by Jefferson (2008) on suggested steps to accelerate the transition towards renewable energy systems. The data and developer interviews suggest that if a clear policy commitment is in place, investors will often be willing to accept these risks, regardless of market history.

Regarding the second preconception that developers tend to exploit forested sites by employing fewer turbines in response to ecological concerns, our data supports this but it does not support our secondary ~~preconception~~ hypothesis that fewer turbines set on higher towers in forested-areas produce more energy per installed kW. We explain this second finding by speculating that the drag effect caused by the trees counteracts the benefits from placing turbines with higher generating capacity on higher towers. This implies that forested and non-forested sites are likely equally attractive to wind developers when it comes to profitability; however, forested sites come with an added risk of public opposition, which Enevoldsen (2016) ~~determined to be due to~~notes is frequently based on ecological concerns. Therefore, policies directed at encouraging forested area developments might need either policies which assure developers of government support in the face of public opposition or higher incentives to offset the elevated risks.

Regarding the third preconception, there does appear to be a sizable ~~lag~~ delay between new turbine model development and adoption in wind farms. This lag appears to be in the range of 3-4 years. The implication is that the wind energy industry and development community are squandering the effectiveness of new technologies due to project ~~lags~~delays. However, it might be that this phenomenon is partly driven by better economics associated with outmoded technologies that come down in price as newer models are introduced. Interviews with developers suggest that if planners wish to encourage faster diffusion of new technologies, they need to consider putting policies in place that mitigate project lags caused by project changes to accommodate newer technologies.

Regarding the fourth preconception that newer technology either promotes greater wind farm production or smaller but more efficient wind farms, our data do not support these hypotheses. Therefore, we conclude that new technology is not necessarily encouraging developers to make more efficient wind farm development decisions. We speculate that the main driver behind progressive increases in wind farm power production over time might be market confidence, but suggest further research to confirm this finding.

These conclusions do point the way towards a series of policy recommendations. If true that developers are not risk averse when entering new markets, then easily accessible high wind speed locations could inspire the significant upsizing of wind farms. Local and national planners could attract and shape future wind development pathways accordingly. That wind farms have less installed capacity in forested areas do suggest that concerns about deforestation and degradation of the environment impact development. This underscores the importance of maintaining rigorous social and environmental impact assessments when wind farms are cited. The fairly significant lag between the adoption of new innovations within the industry and their eventual use in real wind farms three to four years later (on average) also suggests that project development timelines be shortened as much as possible, perhaps further stimulated with supportive policies and regulatory guidelines. The tendency for newer projects to not produce more electricity in aggregate—most likely caused by the fact that the two land based configurations are restricted by a range of parameters for land acquirement to social opposition—also indicates a negative trend that ought to be reversed by either industry or national policy.

In conclusion ~~then~~, our analysis suggests that technology perhaps plays less of a role in guiding wind power diffusion than we might otherwise suspect. Developers appear to exhibit a proclivity to adjust configurations to generate the greatest amount of project value from whatever conditions that they might face. This does not mean that wind power developers will be attracted to any market. Indeed, our interviews suggest that developers are attracted to markets that send clear support signals – market subsidies that are greater than 10 years in length and which have clear procedures established for vetting projects and for issuing building permits. As an example of supportive political incentives, the UK Ministry of Defense assisted the British onshore wind adventure by selling former airfields to wind project developers. However, it is promising to note that once engaged in a market, developers exhibit a tremendous amount of creativity and resilience to make projects work for them.

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